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Electroweak and strong production of SUSY at the LHC

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Summary. — This document outlines the results of the most recent searches for strong and electroweak production of supersymmetric particles performed by the CMS and ATLAS experiments at the LHC at a center-of-mass energy of $\sqrt{s} = 13$ TeV. Both experiments have conducted searches in various final states covering a wide range of signatures.

1. – Introduction

Supersymmetry (SUSY) is a powerful extension of the standard model (SM), able to solve several questions left open by the SM including the ability to explain the hiearchy problem, or the ability to provide a potential dark matter candidate.

In this paper a selection of the most recent searches for strong and electroweak production of SUSY performed by the CMS [1] and ATLAS [2] experiments is presented. The searches use up to $36.1\,\mathrm{fb}^{-1}$ of proton-proton collisions at 13 TeV, collected during 2016 by both experiments.

Most of the searches presented here assume R-parity conservation and thus the presence of two stable neutralinos at the end of the decay chain that escape undetected, yielding sizable missing transverse momentum $p_{\mathrm{T}}^{\mathrm{miss}}$. These neutral, stable, and heavy particles provide an excellent candidate for dark matter and they are often referred as the lightest supersymmetric particle (LSP).

Searches for new physics, and in particular SUSY, usually look for an excess (deviation from the SM prediction) on the extreme tail of some kinematic variable which provides discrimination power against the SM backgrounds. Having found no deviation from the SM prediction during the first year of Run 2, the CMS and ATLAS experiments have designed more sophisticated search strategies to look for any hint of new physics.

In sect. **2** the latest results targeting strong production of gluinos ($\tilde{g}$) or squarks ($\tilde{q}$) are highlighted. In sect. **3**, the most recent results relateds to models of electroweak production of SUSY are discussed. Finally in sect. **5**, a couple of searches for models in which R-parity is not conserved are presented.

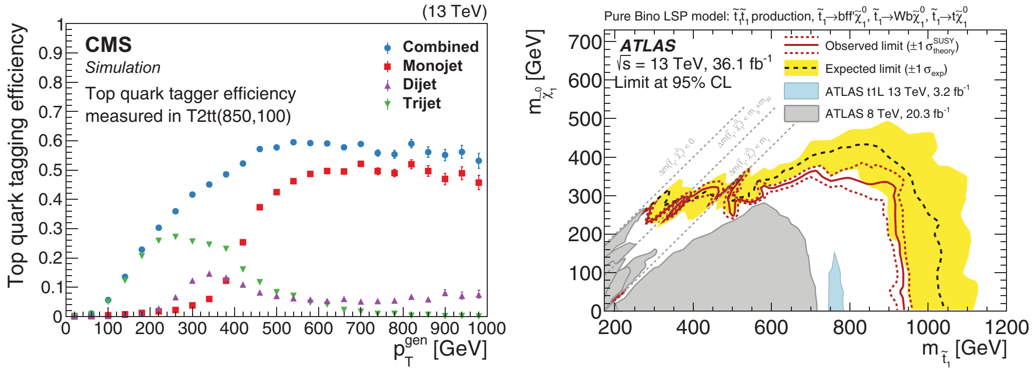

Fig. 1. – Left: efficiency of the top quark tagger as a function of the generator-level top quark p_{T}. The vertical bars indicate the statistical uncertainties. Right: expected (black dashed) and observed (red solid) exclusion limits at the 95% CL in the plane of $m_{\tilde{\chi}_1^0}$ *versus* $m_{\tilde{t}}$ for direct top squark pair production.

2. – Searces for strong production of SUSY

The gluino and squark pair production have been probed extensively by both CMS and ATLAS Collaborations. Generally speaking, these searches provide the highest sensitivity as they profit from the larger cross sections, and they try to be as inclusive as possible, and therefore the results can be interpreted in multiple new-physics scenarios. Most searches carried out by both experiments rely on the discriminating power between the potential signal and the SM background of some kinematic variable and look for an excess on tails of such distribution. Results from these searches with data collected during 2016 probe gluino and squarks masses up to 2 TeV and 1.2 TeV, respectively.

It may well be that the new-physics phenomena is hiding under the overwhelming QCD background with much lower rates. Therefore, more recent searches have developed sophisticated discriminants to beat down the backgrounds. A couple of examples will be discussed in the following lines. One type of novel techniques recently exploited by both collaborations are algorithms to tag top-quarks [5-7]. These tagging methods consider all possible decay modes of the top quark: three jets (b Wjj), two jets (one b and one collimated W), and one jet (one collimated jet), achieving a 60% tagging efficiency considering all three decay modes, see fig. 1 (left).

Using these techniques ATLAS recently presented a search [5] for top squark pair production that provides sensitivity across a wide range of the phase space, from very noncompressed to very compressed scenarios, probing top squark masses up to 1 TeV for a nearly massless neutralino, as shown in fig. 1 (right).

Along these lines, CMS has presented recently a search that involves the tagging of Higgs (H) bosons [8]. The tagging algorithm is designed to identify the decay products of a pair of b quarks clustered into a large jet, resolving the decay chain of the two hadrons and the secondary vertex along the decay. A H boson is identified if two displaced subjets are found. Events with large $p_{\mathrm{T}}^{\mathrm{miss}}$ are then classified according to the number of tagged H bosons. New physics phenomena will appear as a peaking structure in the jet mass distribution around the H boson mass, see fig. 2 (left). No deviation from the SM expectation has been found in this analysis, and results are interpreted on a model of

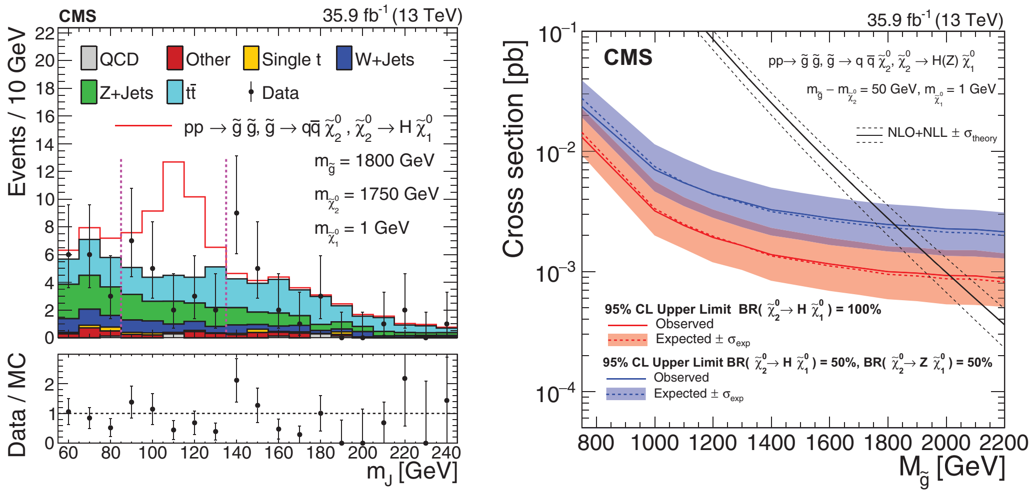

Fig. 2. – Left: observed and expected distributions of the mass of the leading-$p_{\rm T}$ jet for selected events with high values of $p_{\rm T}^{\rm miss}$ and one or H bosons candidates. The shape and composition of SM contributions are modeled with simulated events while the overall normalization is scaled to the prediction in the signal window. A representative signal is shown stacked on top of the backgrounds. The bottom panel shows the ratio of the observed to the expected yields. Right: observed and expected cross section upper limits at 95 CL for two models of gluino pair production. The solid and dashed black lines shows the theoretical gluino-gluino production model cross section with its uncertainty.

gluino pair production, decaying to $\tilde{\chi}_2^0$ and a Higgs/Z boson. According to this scenario, gluino masses up to 1.9 TeV are excluded, as seen in fig. 2 (right).

Another approach recently presented by the CMS Collaboration targets compressed spectra which are typically present in several natural SUSY scenarios. This searches select events with one [9] or two [10] soft leptons($5 < p_{\rm T} < 30$ GeV), and rely on a large initial state radiation (ISR) boost yielding sizable $p_{\rm T}^{\rm miss}$ to trigger the event. These searches are able to probe top squark masses up to 600 GeV in which both the top squark and the LSP have similar masses.

3. – Searches for electroweak production of SUSY

While the largest portion of the SUSY search programs of CMS and ATLAS focus on the strong production of supersymmetric particles, with higher cross-sections, some searches focus on electroweak production of charginos, neutralinos, and sleptons. In an scenario with heavy squarks and gluinos, such production mechanism may be the only experimentally accessible way of producing SUSY at the LHC. Thus, the searches for electroweak production of SUSY have been gaining more and more weight within the search program of both collaborations.

During 2016 and 2017 several searches for pair production of neutralinos and charginos have been carried out by both experiments [3, 4], focusing on multilepton final states, which are the natural final states to look for chargino/neutralino pair production. The chargino/neutralino can decay via sleptons and then to leptons or via W, Z, or H bosons, which subsequently can decay to leptons according to the SM branching fractions. In such decays, very little or no hadronic activity is expected in such decays. Events with

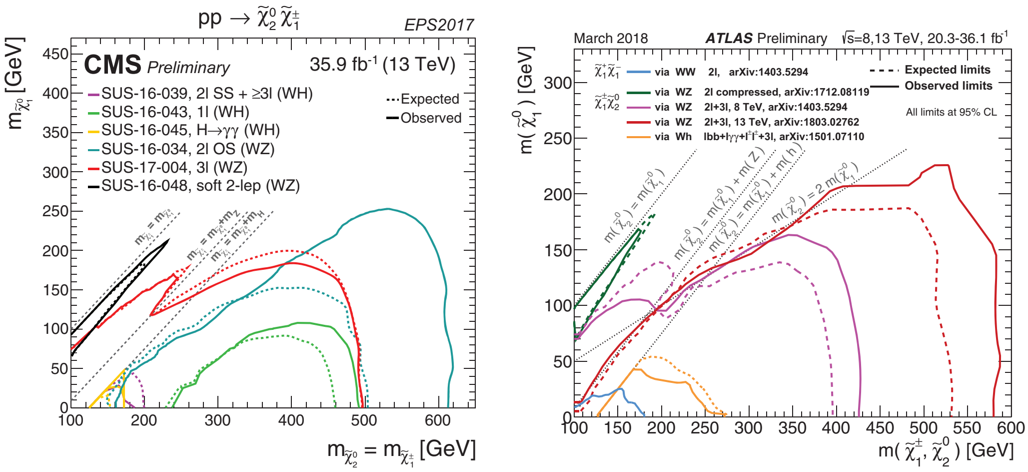

Fig. 3. – The 95% CL exclusion limits on $\tilde{\chi}_1^+\tilde{\chi}_1^-$ and $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production with decays mediated by SM bosons, as a function of the $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^0$, and $\tilde{\chi}_1^0$ masses.

two, three, or more leptons are selected and classified depending on their kinematic properties in order to be sensitive to different mass splittings and scenarios. Results show no deviation from the SM expectations and we are able to probe chargino/neutralino masses from 0.5 up to 1.1 TeV, depending on the model assumptions. A summary of these searches, assuming chargino/neutralino decays via W, Z and H bosons is shown in fig. 3.

Having found no evidence for new physics, more complex searches, targeting more challenging modes, such as slepton pair production, models with gauge-mediated SUSY breaking (GMSB) [11], or compressed scenarios, have been designed by both collaboration and presented recently. A few examples will be briefly discussed in the following lines.

Two searches looking for slepton pair production have been recently presented [12,13]. In the case of CMS, a dedicated search has been performed, while ATLAS presents the result as part of a more general search. The approach is similar in both cases: events with two opposite-sign same-flavor leptons are selected. In addition, only events with M_{T2} above a certain threshold are selected. This powerful variable helps to discriminate between the SM and any new physics scenario as it has and kinematic endpoint around the W mass for dominant SM processes. The search strategy of the CMS analysis then is to classify the events in bins of $p_{\mathrm{T}}^{\mathrm{miss}}$ while ATLAS uses bins of M_{T2} and the invariant mass of the two leptons. No significant deviation from SM expectations has been found by either experiment and the results are used to derive limits on slepton pair production cross sections. Slepton masses up to 500 GeV are probed, as seen in fig. 4.

In some SUSY models, the SUSY partner of the τ lepton, the stau $\tilde{\tau}$, is expected to be lighter than other sleptons such that its mass could be at the electroweak scale. If this is the case, it might either be produced directly or might appear in decay chains of heavier neutralinos or charginos with larger branching fractions compared to the direct stau production. CMS has recently presented a dedicated search for these scenarios [14]. Events with two leptons of different flavor or one e/μ and one hadronically decaying τ lepton are selected and then classified according to the number of jets, $p_{\mathrm{T}}^{\mathrm{miss}}$, M_{T2}, and $\Delta\zeta = \vec{p}_{\mathrm{T}}^{\mathrm{miss}} \cdot \vec{\zeta} - \vec{p}_T^{\ell\ell}$, with $\vec{\zeta}$ the bisector of the two leptons. Results are in agreement with SM expectations. Limits on chargino-neutralino production are set and neutralino

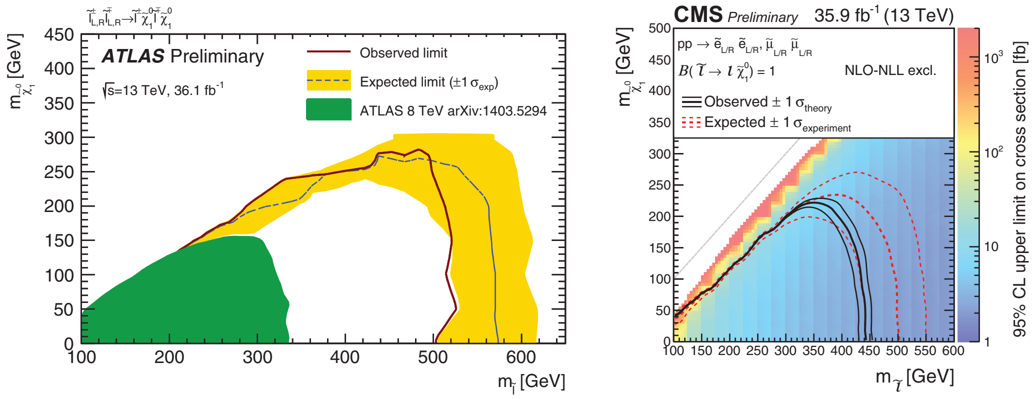

Fig. 4. – Cross section upper limit and exclusion contours at 95% CL for direct slepton production as a function of the $\tilde{\chi}_1^0$ and $\tilde{\ell}$ masses assuming the production of both left- and right-handed sleptons of two flavors.

masses up to 550 GeV are probed. Finally, the result is also used to set an upper limit on the stau production cross section.

4. – Searches with photonic final states

Final states with one or two photons accompanied by large $p_{\mathrm{T}}^{\mathrm{miss}}$ can be also sensitive to both strong and electroweak production of SUSY. In this case we need to assume a GMSB model in which the gravitino is the LSP and the $\tilde{\chi}_1^0$ is the NLSP that decays to a photon and a gravitino. CMS and ATLAS have recently released results of two searches targeting such models.

The ATLAS analysis [15] uses several observables to reject backgrounds while retaining high signal efficiency for different model assumptions: m_{eff} (scalar sum of the transverse energy of all the photons, leptons, jets, and $p_{\mathrm{T}}^{\mathrm{miss}}$), H_T (scalar sum of the p_{T}'s of the jets, photons, and leptons), and R_{T4} (scalar sum of the p_{T}'s of the 4 leading jets). Different search regions (SR) targeting different scenarios are defined. Model-independent limits are derived for each SR and model-dependent ones are computed by a fit of the Sr providing highest sensitivity of the model that is probed. The fit is carried out simultaneously with another region used to constring the SM background prediction. CMS only uses one variable to define the search strategy, $S_T^{\gamma} = p_{\mathrm{T}}^{\mathrm{miss}} + \sum p_{\mathrm{T}}(\gamma_i)$. All search regions are used to obtain the final result. No significant deviation is found by either CMS or ATLAS, and results are used to set limits on the production cross section of supersymmetric particles. Gluino masses up to 2.2 TeV and neutralino masses up to 1.2 TeV are excluded, as it can be observed in fig. 5.

The amount of the collected data opens up regions of the phase space that were not previously accessible, such as the regions in which the chargino and the LSP are nearly degenerated. Such models can yield very soft leptons in the final state. The searches need to rely on the large boost of an ISR jet yielding significant $p_{\mathrm{T}}^{\mathrm{miss}}$ that can be used for triggering purposes. The search strategy followed by CMS [10] and ATLAS [16] is rather similar, events with two opposite-sign soft leptons, large $p_{\mathrm{T}}^{\mathrm{miss}}$ and an ISR jet are selected. Events are then categorized according to their invariant mass and $p_{\mathrm{T}}^{\mathrm{miss}}$ (CMS) or M_{T2} (ATLAS). Results are in agreement with the SM expectations and they are used to set

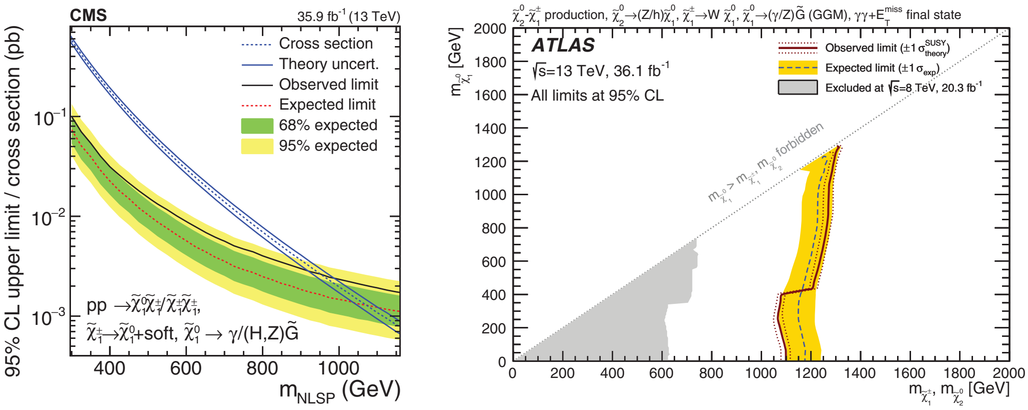

Fig. 5. – Left: observed (black) and expected (red) upper cross section limits as a function of the NLSP mass for a GMSB model of chargino/neutralino production together with the corresponding theoretical cross section (blue). The inner (green) band and the outer (yellow) band indicate the ± 1 and 2 s.d., respectively, of the distribution of limits expected under the background-only hypothesis. The solid blue lines represent the theoretical uncertainty in the signal cross section. Right: exclusion limits in the wino-bino mass plane. The discontinuity at $m_{\tilde{\chi}_1^0} = 400\,\text{GeV}$ is due to the switch between the use of the two search region, one of which exhibits a small excess of observed events relative to the expected SM background.

limits on the cross sections of chargino/neutralino pair production. Chargino/neutralino masses are excluded up to 220 GeV for a mass difference with the LSP of 20 GeV, see fig. 6.

5. – RPV searches

The presence of large values of $p_{\mathrm{T}}^{\mathrm{miss}}$ is the workhorse of most searches for SUSY at the LHC. However, assuming that R-parity is conserved may blind us towards other possible scenarios. Some R-parity conserving searches already provide sensitivity to RPV

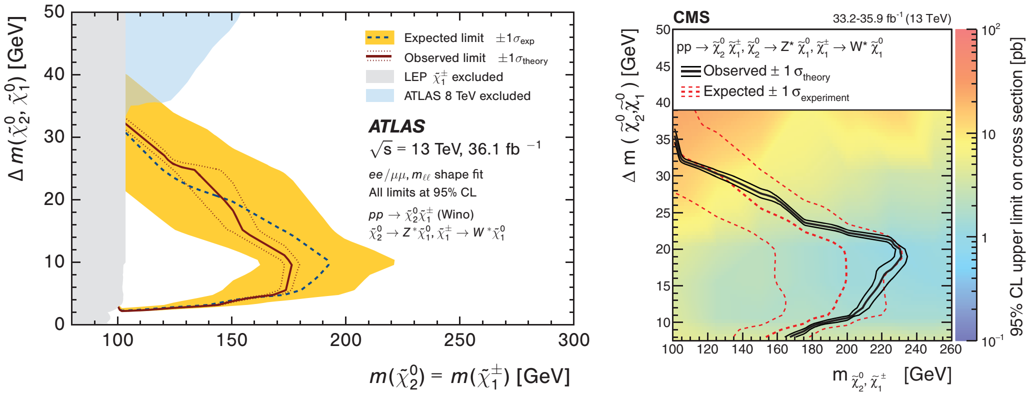

Fig. 6. – The observed 95% CL and expected exclusion contours for the soft-lepton analyses by CMS (right) and ATLAS (left). Results are based on a simplified model of $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to Z^* W^* \tilde{\chi}_1^0 \tilde{\chi}_1^0$ with a pure wino production cross section.

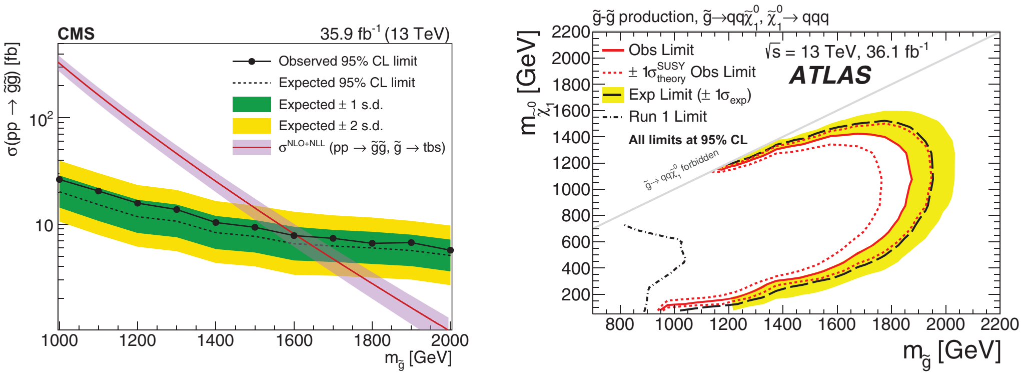

Fig. 7. – Left: cross section upper limits at 95% CL for a model of gluino pair production with $\tilde{g} \to tbs$ compared to the theoretical gluino pair production cross section. The theoretical uncertainties in the cross section are shown as a band around the red line. The expected limits (dashed line) and their ± 1 s.d. and ± 2 s.d. variations are shown as green and yellow bands, respectively. The observed limit is shown by the solid line with dots. Right: expected and observed exclusion contours in the $m(\tilde{g})$-$m(\tilde{\chi}_1^0)$ plane for the gluino cascade decay model. The dashed black line shows the expected limit at 95% CL, while the light yellow band indicating the ± 1 s.d. due to experimental uncertainties. Observed limits are indicated by red curves, where the solid contour represents the nominal limit, and the dotted lines are obtained by varying the signal cross section by the renormalization and factorization scale and PDF uncertainties.

scenarios, however, most of them rely on the presence of large $p_{\mathrm{T}}^{\mathrm{miss}}$ that arise from the two LSP that escape detection and cannot be used for RPV models.

Both CMS and ATLAS have a dedicated search program targeting RPV models. Two recent results, one by CMS, one by ATLAS, will be highlighted here.

The analysis carried out by CMS [17] targets an RPV model of gluino production in which the squarks are much heavier than the gluino and do not play a role in the interaction. Events with four jets and one lepton are selected. Large-R (1.2) jets are built by clustering small-R jets, and we define M_J as a measure of the mass scale of the event. Signal regions are defined in the number of jets and mass of the reconstructed jet. Results are in agreement with the SM expectation and they are used to set limits in a model of gluino pair production, see fig. 7 (left). Gluino masses are excluded up to 1.6 TeV.

A recent result by ATLAS [18] looks for RPV SUSY in events with at least four large-R jets. Apart from the M_J, the search relies on the $\Delta\eta$ between the two leading large-R jets. Signal regions are then defined in the tails of the jet mass distribution. Results are in agreement with the expectation and the signal region with the best expected sensitivity is used for the interpretation. Gluino masses up to 1.8 TeV are probed, see fig. 7 (right).

6. – Conclusions

Several simplified models of both strong and electroweak SUSY production have been probed in various final states with data collected by the ATLAS and CMS experiments at $\sqrt{s} = 13$TeV during 2016. No evidence of physics beyond the standard model has been observed. Exclusion limits have been set on SUSY particles masses in the context of simplified SUSY models. Under such assumptions, gluino and squark masses are excluded up to 2 TeV and 1.2 TeV, respectively. Similarly chargino and neutralino masses are excluded up to 1.1 TeV. With more data collected during 2017 and 2018, further searches for new physics signatures are being developed, and they will increase our knowledge of the existence of SUSY-like particles.

A complete list of results published by the ATLAS and CMS experiments can be found online [19, 20].

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